Secure Programming - Summary

General

Security Goals

The goals of protection, which secure systems should achieve, are:

1. **Confidentiality** Data must be kept confidental, stored encrypted and provided only to authorized clients
2. **Integrity** Input validation, parity bit checking, cyclic redundancy check, cryptographic checking
3. **Availability** "Measures of Nines", f.e. *four nines* == 99.99% availability
4. **Non-repudiation**
5. **Authenticity**
6. **Privacy**

Other requirements

Authentication requirements: Validate an entities claim = verify the legitimacy and validity of the identity claim

Authorization requirements: Confirm that an authenticated entity has the needed rights to perform the requested action

Auditing / logging requirements: Logging message has to answer `who`, `what`, `where` and `when`

Session management requirements: For role-based-access-management and user interaction features

Error and Exception management requirements: Exceptions have to be handled by the application, error messages must only reveal the needed information

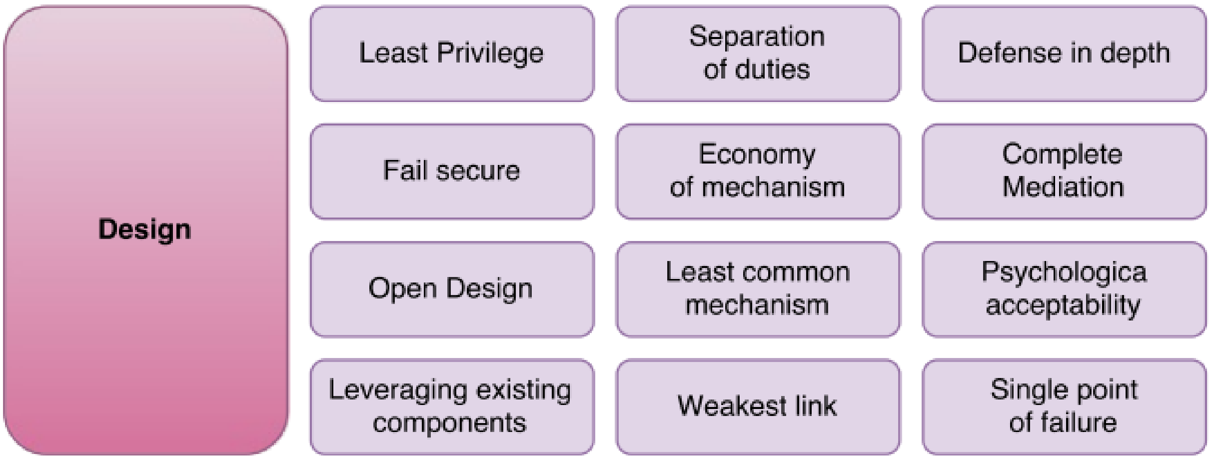
Configuration parameters management requirements: Software configuration parameters have to be protected from manipulation

Sequence and timing requirements: Design flaws in timing or sequencing can lead to race conditions or check / time of use attacks

Archiving requirements: Exist for reasons of business continuity or as a regulatory requirement

Deployment environment requirements: Might affect security requirements

Security Design Principles



- **Least Privilege**: grant only minimum necessary rights needed for the shortest duration possible
- **Seperation of duties**: prevent fraud and errors by dividing tasks and privileges for specific business processes
- **Defense in depth**: layer security defenses
- **Fail secure**: When a system fails, make it fail securely
- **Economy of mechanism**: highly complex sytems are more likely to have security vulnerabilities
- **Complete mediation**: require access checks each time a subject requests access to an object
- **Open design**: security shouldn't depend on the design but on keys and passwords
- **Least common mechanism**: avoid having multiple subjects sharing mechanisms to grant access to a resource
- **Psychological acceptability**: Resources should still be easily accessible to prevent users from disabling security mechanisms
- **Leveraging existing components**: reuse existing components to decrease the introduction of new vulnerabilities
- **Weakest link**: Attackers are more likely to attack weak spots than fortified components
- **Single point of failure**: a *SPOF* can make the application unavailable, can be avoided by using redundancy

Initialization

Safe Initialization / System Environment

Environment variables can be accessed by written code and potentially be misused / introduce security flaws.

Solution: Sanitzing **PATH** and **IFS** variables.

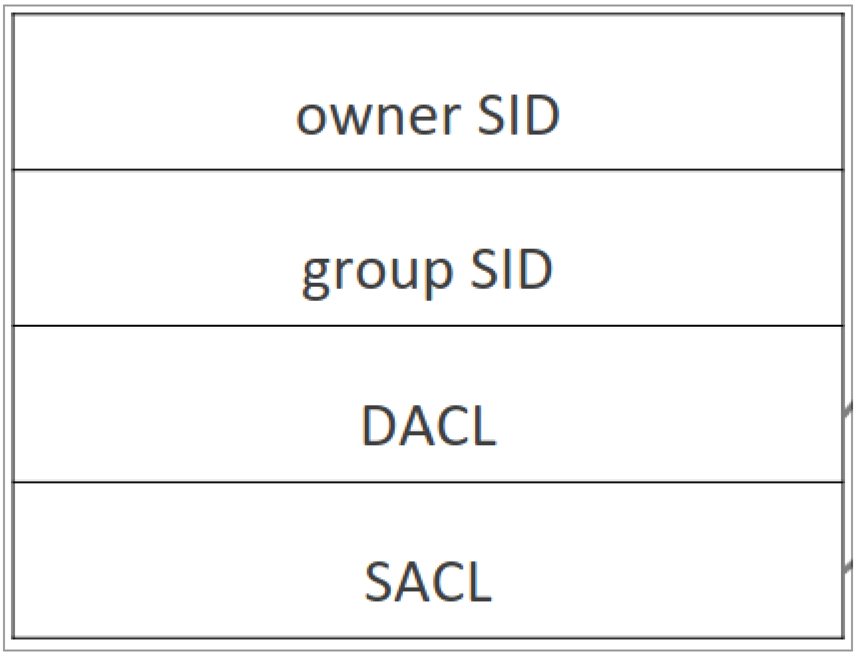
- **PATH**: locate executables in the system
  - never include relative paths
  - force the setting of the PATH environment variable to only needed values
- **IFS**: used by many shells to determine which character seperates command-line arguments
  - should be set to something sane (e.g. space, tab, newline)

Authorization on Windows

Access Management

Windows manages access rights in an *Access Control List* saved in security-descriptors in the *Master File Table*

Windows



- **SID**: system wide unique security ID
- **DACL**: discretionary ACL = list of ACEs (Access Control Elements with allow/deny)
- **SACL**: system ACL, specifies operations to log and audit

Privilege Restriction in Windows through Access Tokens

Every thread / process started in the user context has a copy of the access token that's been created after user login. Processes that shouldn't be able to access some functionality only get required rights / restricted tokens that have been created through the `CreateRestrictedToken` function:

- removes privileges from a token
- applies the *deny-only* attribute to SIDs
- specifies a list of restricting SIDs

Access Tokens contain:

- Security identifier (SID) of the user & user groups
- SID of logon session
- list of privileges
- owner SID
- TSID for primary group
- default DACL
- access token source
- access token primary or impersonation

- optional list of restricting SIDs
- impersonation levels
- statistics

Input Validation

Safe assumptions are essential:

- input is guilty until proven otherwise
- prefer rejecting data to filtering data
- policy decisions based on a "default deny" rule
- do not accept commands from the user unless you parse them yourself
- perform data validation at input points and component level

Rules of Input Validation

1. **Define what you expect**: What Purpose, Format, Size for the requested input, which conversion is done?
2. **Canonicalize (Seperation of Concerns)**
3. **Check that input meets expectations**
4. **Manipulate input or drop it if expectations aren't met**

Input Validation Problems

URL

1. **Unsafe character encoding**: Multiple encoding of unsafe characters may lead to ambiguities (Mehrdeutigkeit) in URLs - this can lead to potentially undefined states.
2. **NULL-termination of C-strings**: can be encoded anywhere in the URL #

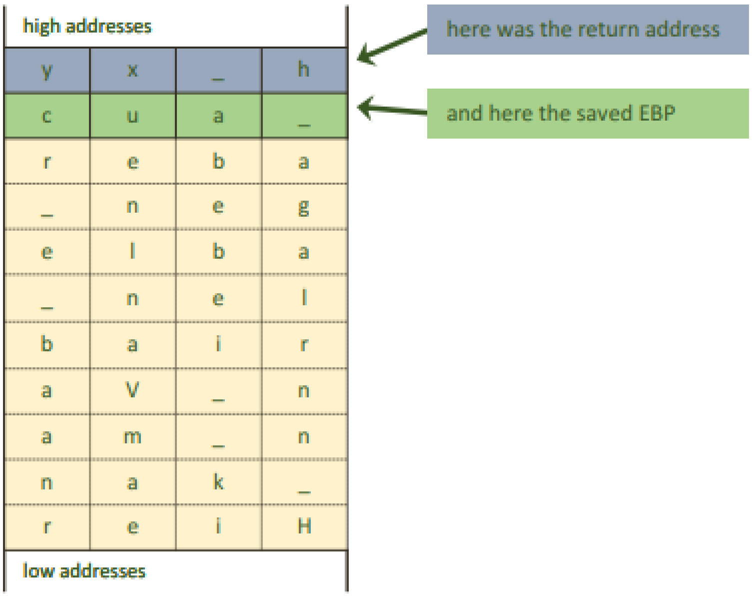
Strings

Common Errors:

- unbounded stream from stdin ⟶ limit size
- unbounded string copy and concatenation ⟶ dynamic allocation
- extracting characters from `cin` into character array ⟶ use maximum buffer size
- writing exactly as many characters than space causes buffer overflow, because strings are null-terminated in C (`\0`)

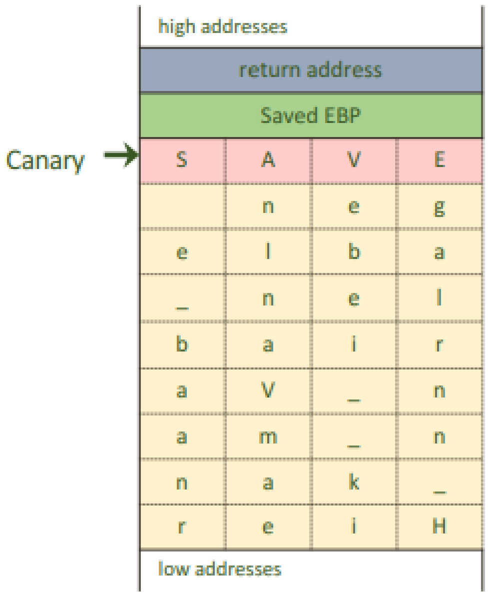
When more data is written than allowed:

- saved EBP and return address are overwritten (in C and C++)



- return address can be modified to point to a malicious program or just destroyed to produce DOS (Denial of service)

Solutions:



- **Canaries**:
  - *canary* value at the end of allocated memory
  - when destoryed ⟶ buffer overflowed
  - *BUT*: DOS still working
- **Bounds checking**:
  - compiler-based technique
  - adds run-time bounds information for each allocated block of memory
  - checks pointers against run-time bounds during run-time
- **AddressSanitizer**: (implemented in clang or gcc)
  - detects all kinds of memory-corruption bugs
  - Downside: performance overhead
  - checks for example: heap use after rfree, heap and stack buffer-overflow

- **OS-based-defenses**:
    - Non-executable stack
        - mark data in stack as non-executable
    - Adress-Space-Layer-Randomization (Unix and Win)
        - randomize address space
        - addresses can only be guessed
    - Sandboxes and compartment based OS extensions
        - execute vulnerable components in protected areas

Also always use safe options during coding:

- `printf(string)` ⟶ `printf("%s", string)`
- `fprintf(stderr, string)` ⟶ `fprintf(stderr, "%s", string)`
- `snprintf(puffer, sizeof(puffer), string)` ⟶ `snprintf(puffer, sizeof(puffer), "%s", string)`

Integer

Errors:

- Integer Overflow
- Sign Errors (Signed or Unsigned)
- Truncation Errors (Kürzungsfehler)

Mitigation strategies:

- Range checking
- Strong typing
- Compiler options
- Arbitrary precision arithmetic
    - GNU Multiple Preciison Arithmetic Library (GMP)
    - Java BigInteger

Additional Topics - Input Validation

- Validating Email-Addresses
    - check against RFC 822
- Cross Site Scripting
    - Refuse to accept anything that look like HTML
    - Escape special characters
- SQL-Injection
    - Restrict user input to the smallest character set possible, refuse anything else
    - Escape character that have special significace to SQL (f.e. `;`, `=`, `""`)

> **ALWAYS**: default deny

Randomness

Used for creation of keys, nonces, initialisation vectors, salts, canaries, ...

Randomness in computers:

- Get data from an unpredictable hardware-source
- Use numbers seed to create much larger number or subsequent pseudo-random-numbers
- from real world
    - quantum vacuum fluctuation
    - radioactive decay
    - photonoic emission
    - outcome of qunatum measurement of equal probability

Security considerations

Security issues with randomness:

- Weak generation:
    - WPS on cheap WIFI-APs
    - Weak generation in programming (`rand()` in C & C++)
- Manipulation:
    - insecure standards (NSA manipulated RSA RNG-standard)
    - manipulation of RNG in OS
        - through malware
        - hardware RNG manipulation
- Special case: virtual machines
    - source of entropy (Informationsdichte) not under control

> Encryption needs a key of *good* randomness. Non randomness of RNG create most weaknesses of encryption.

Possible RNGs

- Noncryptographic pseudo RNGs
    - attacker could predict the output of such generators
- Cryptographic pseudo-random number generators (CPRNGs)
    - single secure seed ⟶ generate as many unguessable numbers as necessary
    - secure for most use cases, but has to be **securely seeded**
    - Sources:
        - random infrastructure in OS:
            - *Unix*: `/dev/random`
            - *Windows*: `CryptGenRandom()`
        - CPRNG systems like `cprng-aes` or `openssl`
        - exteernal sources of random-numbers if applicable
- Entropy harvesters
    - try to gather entropy from other sources and present it directly, therefore sometimes *true* RNG
    - expected to bes seucre under most circumstances
    - incredibly slow to produce data
    - entropy data has to be postprocessed with cryptographic method to remove statistical bias

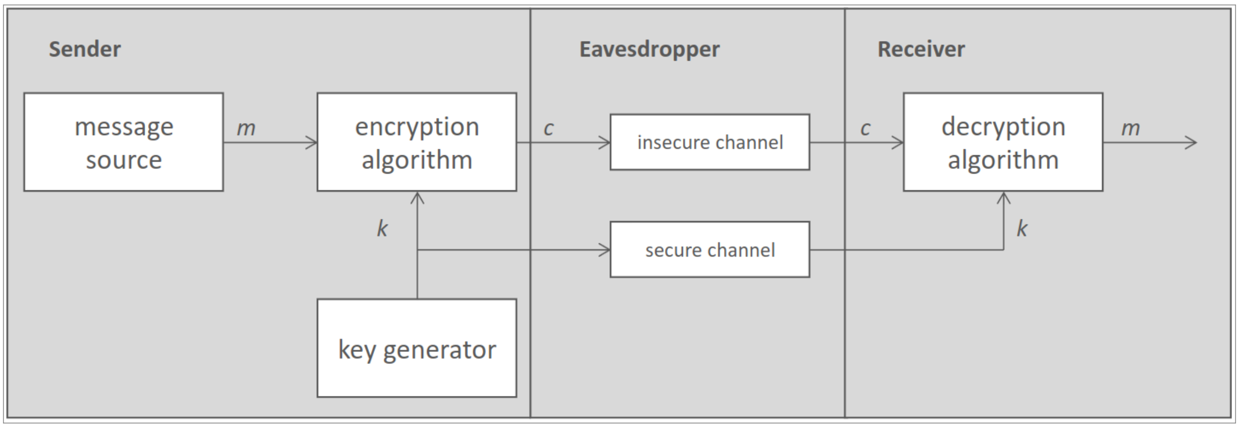
- Quantum RNGs
  - quantum mechanical random processes to generate random numbers

Encryption Techniques

Kerckhoff-Principle: Quality of Cipher is only dependent on the quality of the secret.

Symmetric Encryption

Symmetric encryption by using a single key for encryption and decryption.



Private-Key Encryption

Cipher Types:

- **Stream ciphers**: Substitute data bit by bit or byte by byte with pseudo-random data (*SNOW 2.0, MUGI*)
- **Block ciphers**: Encrypting fixed size chunks of data (*AES*)

> General recommendation: always use **AES**

Key length should be *128+bit* - secure enough for a long time. If RNG isn't trusted, longer keys have more entropy and are therefore more secure (but slower).

Current Cipher mode of choice is **GCM** (RFC 4106), recommended by *NIST* and offering integrity.

Integrity through hashing

To add integrity to a message, add message hash to communication. Receiver decrypts message and creates hash ⟶ when hashes match, message wasn't changed

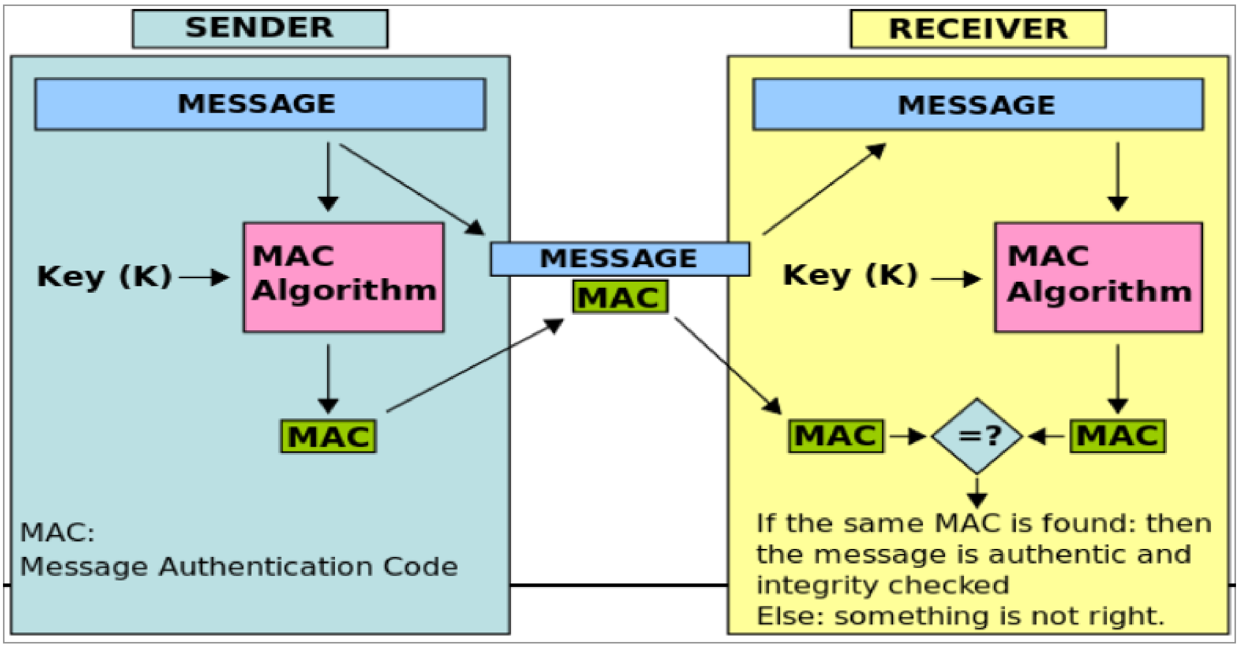
Requirement for hash-functions:

- **One-wayness**: can't compute plaintext value from generated hash
- **Noncorrelation**: Input bits and output bits shouldn't correlate
- **Collision resistance**: should be infeasible to find two plaintext values that produce (roughly) the same hash

> Recommended hashing algorithm: **SHA (256+)**

MAC - Message authentication codes

Hash functions that take a message and a secret key as input. The output can only be produced whithout posessing the secret key.



Possible MACs: OMAC, CMAC, HMAC

Asymmetric Encryption

Key distribution is constant source of insecurity. Solution for this problem:

1. Every person being part of the communication creates a pair of keys for en- & decryption.
2. Personal encryption key get's shared between all members.
3. Encryption of personal messages can be done by anyone, decryption can only be done with private key.

This is called **Public Key Cryptogarphy**, where K_e is the public and K_d is the secret key.

RSA

1. Key Generation:
   - choose p & q, $n = p * q$, $\phi(n) = (p-1)(q-1)$
   - choose $1 < e < \phi(n)$, $gcd(e, \phi(n)) = 1$
   - choose d, so that $(d * e) mod\ \phi(n) = 1$
2. Encryption: $C = P^e mod\ n$
3. Decryption: $P = C^d mod\ n$

The pair (n, e) is shared as the public key.

Security considerations

Types of attacks:

- derive K_d from K_e (when N from RSA can be factorized) $\longrightarrow$ RSA is as secure as factorization
- derive m (message) from c (ciphertext) $\longrightarrow$ **RSA-Problem**

- known plaintext attacks
- timing attacks
- sidechannel attacks

Integrity

Integrity is added through hashes:

1. A function pair is determined: S for hashing with K_d, V for verfiying the hash with K_e
2. Sender adds hash of $S(M, K_d)$ to encrypted message C
3. Receiver proofs that the sender knows the private key through $V(C, S, K_e)$

This is called **Digital Signature**.

Digital Signature

Signing Function:

1. hash plaintext message
2. encrypt hash with private key $K_d(p_1)$
3. message with public key $K_e(p_2)$
4. send encrypted message and encrypted hash to receiver
5. decrypt message with $K_d(p_2)$, calculate hash
6. decrypt transmitted hash with $K_e(p_1)$
7. compare results

Keys & Secrets can be exchanged through the **Diffie-Hellman Keyexchange**:

- choose prime numbers p and g
- Alice and Bob choose their own private keys x, compute public keys $X = g^x mod\, p$
- Share $X(Alice)$ and $X(Bob)$, compute secret $s = X^x mod\, p$

Usage

Private Key-Encryption is about 1000 times slower than symmetric encryption. It's mostly used to encrypt symmetric keys, which then can be transferred over insecure channels.

Authentication

Proof, that you are the one that you claim to be.

1. **Things you know**: passwords, PIN, passphrase, ...
2. **Things you have**: ATM cards, ...
3. **Things you are**: fingerprints, voice analysis, ...

Requirements:

- Practicality of deployment
- Usability
- Use across applications

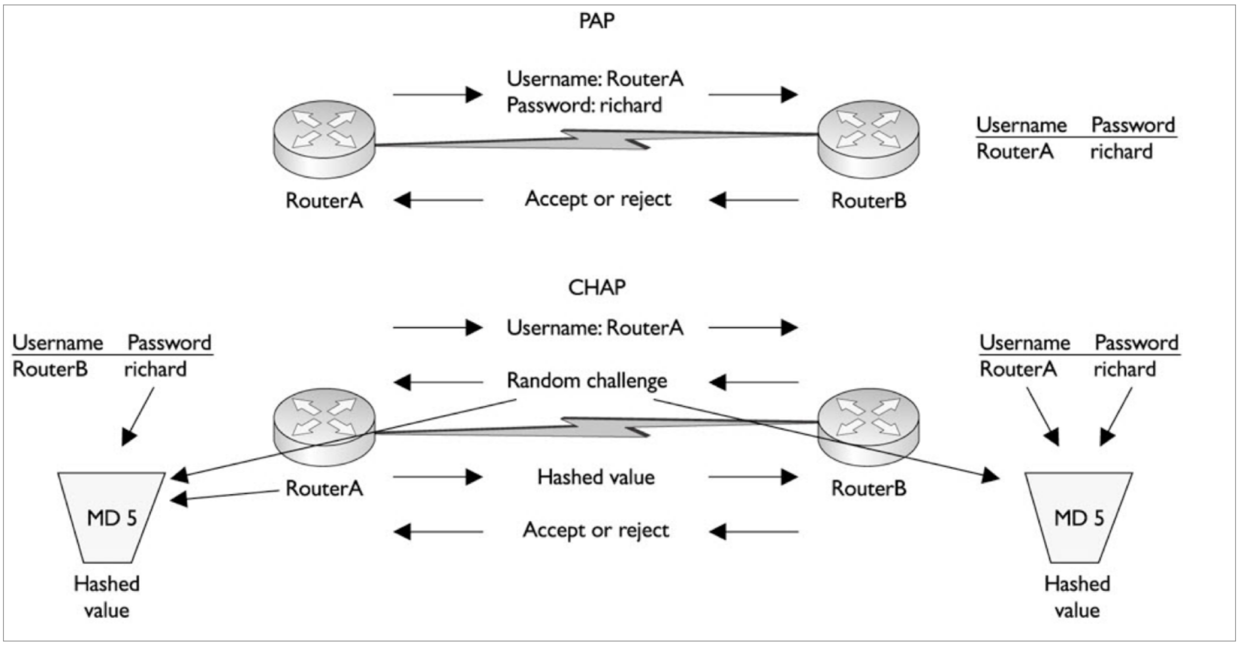
- Patents
- Efficiency
- Security
- ...

Popular technologies

- Password
- PKI
  - SSL certificate based checking
  - public key exchange
- Directory based mechanisms
  - LDAP
  - Kerberos
- Bimoetric authentication

Password checking

Never send unencrypted passwords over the internet!



- agree on hashing / encryption algorithm prior to password exchange
- use zero knowledge mechanisms, e.g. Fiat-Shamir-Feige:
  - $N = p * q$
  - $v = s^2 mod\ N$ (Pair **(v,N)** is the public key of A)
  - $x = r^2 mod\ N$, send x to B
  - B sends bit to A, if bit == 0 respond r, else $y = (r * s) mod\ N$
  - B checks response by calculating it reverse

PKI = Public Key Infrastrucutre

Consists of:

- **Certification Authority (CA)**: issues and signs certificates

- **Registration Authority (RA)**: guarantees public key belongs to specific entity
- **Directory Service**: distributes certificates and CRLs
- **Validation Authority (VA)**: real-time validation of certificates

Gets implemented by the Needham-Schroeder protocol:

- authentication server communicates with the server
- the server authenticates itself and the client it's communcating
- authentication through secret and symmetric keys

Directory services

Directory services store personal information and can also be used to store authentication credentials. The most poular protocol is **LDAP**.

Kerberos

Client has to authenticate with an authentication server first. Next the ticket granting server grants the client a ticket, which he can use to communicate with a server in a certain timerframe.

Single-Sign-On

SAML-Protocol is used to exchange information between policy-enforcement- and policy-decision-points.

XACML is used to specify access policies.

Alternatives: OAuth and OpenID

Programming

Secret information has to be kept out of source code.

- changing secret information would be difficult
- easy to attack by anyone who has the binary

Alternatives:

- Ask the user who is starting the binary ⟶ are access rights sufficient
- Store secret in seperate file or database and secure that
- Encrypt and ask user or OS for key
- Use existing external mechanisms for authentication (LDAP, Kerberos, ...)
- Use already existing credentials
- Use hashing wherever useful ⟶ hashing is irreversible, salted hash is enough for authentication

Secret storing

During execution, the secret can be found / stored in CPU, RAM and hard disk.

After execution, the CPU storage is flushed, but the RAM storage has to be overwritten.

After system shutdown, only the hard disk is a possible storage, but the RAM could be attacked by cold boot attacks.

To be safe, make sure to **delete and overwrite memory** after secrets are not needed anymore. Also try to lock the address-space during execution, try to use further OS-based memory and process protection technologies.

> If your OS is broken, everything is broken!